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# Thomson scattering measurements from asymmetric interpenetrating plasma flows[a)]

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Imaging Thomson scattering measurements of collective ion-acoustic fluctuations have been utilized to determine ion temperature and density from laser produced counter-streaming asymmetric flows. Two foils are heated with 8 laser beams each, 500 J per beam, at the Omega Laser facility. Measurements are made 4 mm from the foil surface using a 60 J $2\omega$ probe laser with a 200 ps pulse length. Measuring the electron density and temperature from the electron-plasma fluctuations constrains the fit of the multi-ion species, asymmetric flows theoretical form factor for the ion feature such that the ion temperatures, ion densities and flow velocities for each plasma flow are determined.

## I. INTRODUCTION

Thomson scattering[1] (TS) has demonstrated its utility as a powerful diagnostic for understanding plasma conditions in high-energy density physics experiments. This technique provides a non-invasive method to measure localized plasma parameters such as electron and ion temperature, electron density, plasma flow, and ionization state[2–4]. It has also been used to determine ion species fraction[5,6]. Recent experiments focused on the study of counter-streaming laser plasmas[7–10] to generate collisionless shocks have motivated the development and demonstration of a TS treatment for asymmetric, counter-streaming, interpenetrating plasma flows.

Thomson scattering[1,11,12] is used to characterize laser-produced[13] plasma flows by fitting the measured data with the TS cross-section defined by the dynamic structure factor, $S(\mathbf{k},\omega)$. The dynamic structure factor has been written to include asymmetric, multi-ion species, interpenetrating flows with different ion temperatures and densities. It is,

$$\frac{|\epsilon|^2}{2\pi}S(\mathbf{k},\omega) = |\epsilon-\chi_e|^2 F_e\left(\frac{\omega}{k}\right) + |\chi_e|^2\frac{(k\lambda_{De})^2}{\pi T_e}\sum_{direction}\sum_{j\in ions}\frac{T_{j,D}\mathrm{Im}\chi_{j,D}}{\left(\omega-\vec{k}\cdot\vec{V_D}\right)} \tag{1}$$

where $\omega$ is the frequency of the scattering wave, $\epsilon = 1+\chi_i+\chi_e$, $\chi_i = \sum\sum\chi_{j,D}$ and $\chi_e$ are the ion and electron susceptibility respectively,

$$\chi_{j,D} = \frac{-0.5}{(k\lambda_{j,D})^2}\left(\mathrm{Re}Z'_{j,D}+i\mathrm{Im}Z'_{j,D}\right) \tag{2}$$

is the ion susceptibility of species $j$ in direction $D$, and $Z'$ is the plasma dispersion function. Double sums are sums over the ion species and the flow directions. For a maxwellian, $F_e = \frac{(k\lambda_{De})^2}{\pi\omega}\mathrm{Im}\chi_e$, $V_D$ is the flow velocity of flow $D$, $T_{j,D}$ is the ion temperature of species $j$ in flow $D$, $n_e = \sum\sum Z_{j,D}n_{j,D}$, $Z$ is the average ionization state, $n_{j,D}$ is the ion density, $\vec{k} = \vec{k}_s - \vec{k}_0$, $\vec{k}_o$ is the wave number of probe beam, and $\vec{k}_s$ is the wave number of the scattered light. The ion temperatures ($T_{j,D}$), the plasma flow velocities ($\vec{V_D}$), and the ion densities ($n_{j,D}$) are then determined with high accuracy by comparing the TS cross section, calculated using Eq. 1, to the scattered spectra.

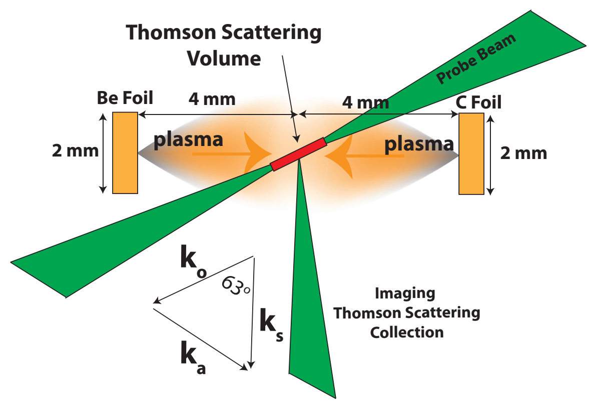


FIG. 1. The experimental configuration is shown. The target foils are heated for 1 ns with 8 drive beams per foil (not shown). The plasma is then probed 5 ns after the rise of the heater beams 4 mm from the foil surfaces using an imaging Thomson scattering diagnostic. The Thomson scattering k-vector diagram is also shown.

## II. EXPERIMENTAL SETUP

Two foils, one Berylium and one Carbon, are positioned 4 mm from the target chamber center (TCC) as shown in Figure 1. The foil is 2 mm in diameter and 0.5 mm in thickness. It is heated with eight 351 nm, laser beams on the Omega laser system. Each beam delivers 500 J in a 1 ns square pulse. The beams use

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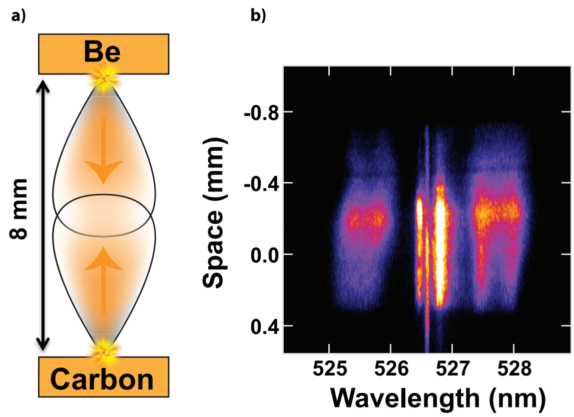


FIG. 2. a) The experimental schematic and b) the spatially-resolved Thomson scattering spectra are shown. Due to the scattering and target configurations the blue shifted scattering feature is dominated by the beryllium plasma flow and the red shifted feature by the carbon flow. Non-Thomson scattered light from specular reflections from the targets is observed between 526 and 527 nm.

distributed phase plates to produce supergaussian focal spots with a supergaussian exponent of 4.3 and a diameter of $\sim$250 $\mu$m. This results in an overlapped laser intensity of $\sim 8\times10^{16}$ W/cm$^2$ with a smooth spatial profile.

The TS diagnostic was configured for imaging mode[14], the scattered light is spatially resolved for $\sim$1.5 mm along the 527 nm probe beam which is focused at TCC. The probe beam has a 70 $\mu$m diameter focal spot and a pulse length of 200 ps. A total probe energy of 60 J was used. The Thomson scattered light is collected 116.8° relative to the probe resulting in a probed k-vector normal to the target surface, as shown in Figure 1.

## III. RESULTS

The raw TS data is shown in Figure 2 b). Two doppler shifted TS signals are measured from the interpenetrating plasma flows. The beryllium dominated flow is blue shifted and measured between 525 and 526 nm. The carbon dominated flow is measured between 527.3 and 528.3 nm. Probe light specularly reflected from the target foils is observed between 526.2 and 527.2 nm. The beryllium flow originates at -4.0 mm and the carbon flow at +4.0 mm. As the flows propagate and interpenetrate the ion temperature increases[15]. This is evident in the scattered spectra where close to the source of the flow two distinct peaks are observed (528 nm, 0.2 mm for carbon) and once the flow passes the mid-plane a single peak is observed (525.5 nm, 0.2 mm for beryllium).

Figure 3 shows the experimental spectra at 0.2 mm compared to the Thomson scattering form factor (Eq. 1) for a series of ion temperatures. The intensity ratio between the two features is used to determine the ion density of the respective flows. Decreasing the ion temperature results in a more collective spectrum[16] eventually producing a spectrum with 4 distinct peaks. For large ion temperatures two peaks would be present, one for each flow material. For the case in Figure 3 the beryllium feature is a single peak due to the measured ion temperature of 900 eV. The carbon ion temperature is lower at 500 eV producing a carbon feature with two peaks.

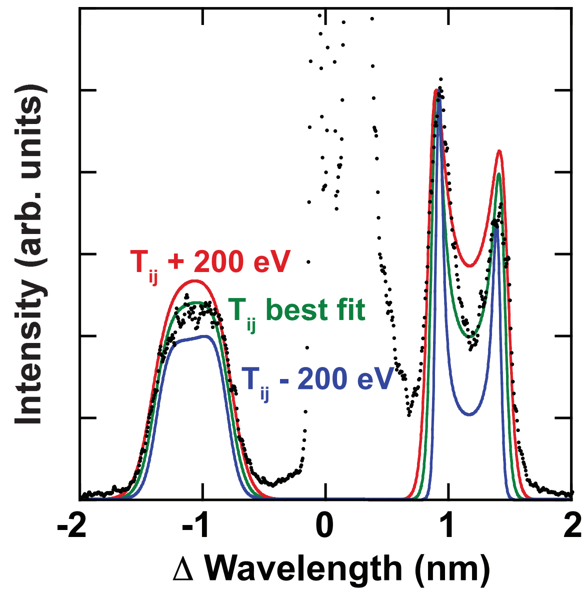


FIG. 3. The Thomson scattering cross section defined by Eq. 1 is compared to the experimental data (black dots) for a range of ion temperatures. The wavelength is plotted as a differences from the incident probe wavelength of 526.5 nm. The best fit (green line) to the experimental data at 0.2 mm using an electron temperature of 600 eV and an electron density of $5.0\times10^{18}$ cm$^{-3}$, has a carbon ion temperature of 500 eV and a beryllium ion temperature of 900 eV. The carbon ion density is $5.5\times10^{17}$ cm$^{-3}$, and the beryllium ion density is $4.2\times10^{17}$ cm$^{-3}$. Changing both ion temperatures by +200 eV (red line) or -200 eV (blue line) produces a form factor that is no longer in agreement with the measured data.

## IV. CONCLUSIONS

Thomson scattering is a powerful diagnostic for characterizing laser plasmas. It has been used extensively to measure the ion and electron temperatures, the electron density, and the plasma flow velocity. Recent experiments have demonstrated TS from high-velocity interpenetrating plasma flows of different ion species. Using the TS form factor it is possible to measure the ion temperatures and densities for the individual flows. This work was performed under the auspices of the Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344.

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